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Analysis of Cascade Control Structure in Train Dynamic Braking System

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***Abstract*—**In recent years, increasing the usage of railway transportations especially in developing countries caused more attention to control systems railway vehicles. Consequently, designing and implementing the modern control systems to improve the operating performance of trains and locomotives become one of the main concerns of researches. Dynamic braking systems is an important safety system which controls the amount of braking torque generated by traction motors, to keep the adhesion coefficient between the wheel-sets and rail road in optimum bound. Adhesion force has an important role to control the braking distance and prevent the wheels from slipping during the braking process. Cascade control structure is one of the best control methods for the wide range of industrial plants in the presence of disturbances and errors. This paper presents cascade control structure based on two forward simple controllers with two feedback loops to control the slip ratio and braking torque. In this structure, the inner loop controls the angular velocity and the outer loop control the longitudinal velocity of the locomotive that its dynamic is slower than the dynamic of angular velocity. This control structure by controlling the torque of DC traction motors, tries to track the desired velocity profile to access the predefined braking distance and to control the slip ratio. Simulation results are employed to show the effectiveness of the introduced methodology in dynamic braking system.

***Keywords*—**Cascade control, dynamic braking system, DC traction motors, slip control.

I. INTRODUCTION

NOWADAYS, due to the widespread usage of railroad vehicles, using of modern control systems to improve the performance of these transportation systems has become more important. One of these cases is dynamic braking control system as one of the subsystems in trains. In order to use the slip control systems as an active safety system in railroad transportation [1], a wide field to study for researchers is produced. Due to the complexity of dynamic braking control system, choosing a proper and accurate control system with considering all effective and vital parameters in the braking process and different conditions is highly important. Due to the important role of traction motors in diesel locomotives during the braking process and direct connection between the armature current of the motor and tractive force, finding the best control structure to control the dynamic braking system is really significant. Among the control structures, cascade control method is one the best control structure particularly in the presence of disturbances and noise.

In recent years, several different researches in slip control and control dynamic braking system have been done. Dynamic braking as an active safety system has been introduced in [1]. At first part of this study, the authors presented the dynamic equation of the hydraulic antilock brake system of vehicles. Then all the results of the simulations have been evaluated with the practical experiences. In [2], dynamic braking control in locomotives is considered with accurate estimation of braking distance in different conditions. This study evaluated the performance of DC and AC traction motors in the braking process. Reference [3] expressed the theoretical and practical perspectives of slip control in diesel locomotives with DC traction motors. In this paper, performance of different type of DC traction motors has been considered. In [4], a dynamic model of the wheel-sets of a high speed train and equations of the adhesion coefficient have been presented. Then, by evaluating of the slip curve and choosing the proper area to occur the maximum adhesion coefficient, a robust adaptive control system has been designed. Reference [5] introduced different slip control methods with evaluating the transported adhesion force between the wheel-sets and the rail. In [6], an adaptive controller for sliding mode to control the value of the slip parameter ratio at the desired value has been designed in trains. Reference [7] proposed sliding mode controller by considering robustness for braking control system, because of the uncertainties that results in from nonlinear characteristics of wheel to rail adhesion force and braking material friction coefficient. In [8], cascade control structure has been described usefully with different practical examples to use.

In this study, the control of DC traction motors to obtain the best slip ratio in a locomotive is presented. In this paper, we present the formulation and simulation of dynamic barking system and DC traction motors with shunt and separate excitations. We introduce cascade control structure by designing two *PI* controllers with the feedback of longitudinal velocity and angular velocity of a wheel-set and by comparing these items with the desired velocity profile. Simulation results are presented to show the effectiveness of this control strategy.

II. DYNAMIC BRAKING MODELING

In this section, as it is shown in Fig. 1, dynamic braking equations are presented for a wheel-set of a locomotive.

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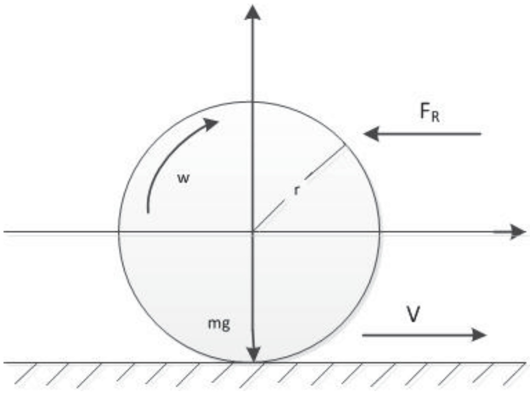

Fig. 1 Free forces diagram for a wheel-set of a locomotive

As it is shown in Fig. 1 [2], [4], dynamic equations of motion during the braking process for a wheel-set of the locomotive can be defined as:

$$m\dot{v} = -\frac{\tau_L}{r} - F_{Ra} \tag{1}$$

$$j_R\,\dot{\omega} = -G_R\tau_M + \tau_L \tag{2}$$

$$\tau_L = \mu(\lambda).m.g.r \tag{3}$$

where, resistant force, F_{Ra}, in the direction of motion can be presented as (4):

$$F_{Ra} = cv^2 + bv + a \tag{4}$$

Equation (1) shows the relation of longitudinal velocity of the locomotive and τ_L is the torque that help the locomotive to stop during the braking process. Equation (2) shows the relation with the angular velocity of a wheel and motor torque, where the gear ratio of transmission system is G_R and j_R is the total moment of inertia. Parameters m and r in (3) are the quarter mass of locomotive and the radius of the wheel. In (4), parameter a is related to the mass of the locomotive and the number of axes, parameter b is used for the flange resistance coefficient and parameter c is used for the aerodynamic resistance force coefficient. The equation of the adhesion coefficient (μ_λ) and its relation with slip angular velocity is defined in (5) where the parameters a', b', c' and d' are designed for the dry rail surface condition [4] in Table I. ω_s as the slip angular velocity is defined in (6). Slip ratio during the braking process is defined as (7).

$$\mu(\lambda) = c'e^{-a'\omega_s} - d'e^{-b'\omega_s} \tag{5}$$

$$\omega_s = \frac{v}{r} - \omega \tag{6}$$

$$\lambda = \frac{v - r\omega}{v} \tag{7}$$

Adhesion coefficient based on slip ratio curve for a locomotive is shown in Fig. 2 and the best area to have a good adhesion coefficient to prevent slipping and having a best friction force happens when the slip value (λ) is between the 0.05 up to 0.1.

TABLE I
DYNAMIC BRAKING EQUATION PARAMETERS

parameters	abbreviation	value
m	Mass of locomotive	40 tons
r	Wheel radius	0.5 m
j_R	Wheel inertia	125 (kg.m^2)
G_R	Gear ratio	2
a	Resistance force parameters	0.78608
b		0.0305
c		0.00015468
a'	Parameters of adhesion coefficient	0.54
b'		1.2
c'		1
d'		1

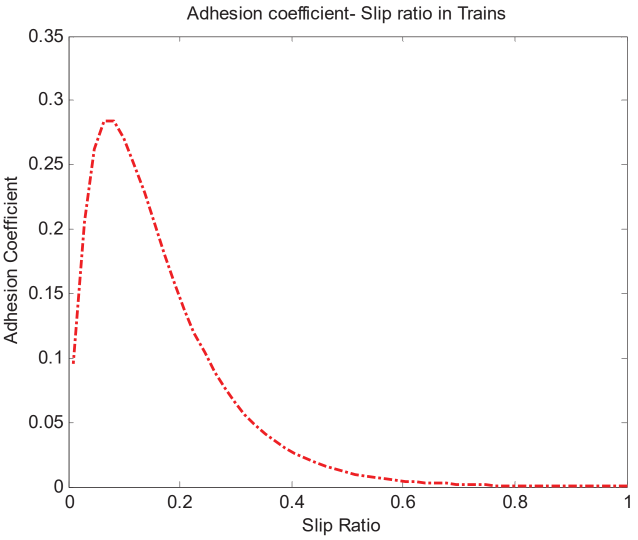

Fig. 2 Relation between adhesion coefficient and slip ratio

III. CASCADE CONTROL STRUCTURE

Among the control methods, cascade control structure is one of the best control methods particularly in the presence of disturbances and errors. In this paper, we present a cascade control structure with two feedback control loops. The inner loop which is called primary loop is faster than the outer loop as the secondary loop and feedback the angular velocity of the wheel set. The outer loop control the longitudinal velocity of the wheel set to track the desired velocity profile and have adhesion coefficient in the desired operational area. This cascade control structure, given in Fig. 3, shows the scheme of the control method in this system that can control DC traction motors torque to produce sufficient braking force and control the amount of slip ratio at the desired value.

In the next sections, simulation results are considered for the two types of DC traction motor excitations. At first, the Shunt excited DC traction motor is evaluated by open loop and closed loop system and then a separately excited DC traction motor is considered with similar conditions.

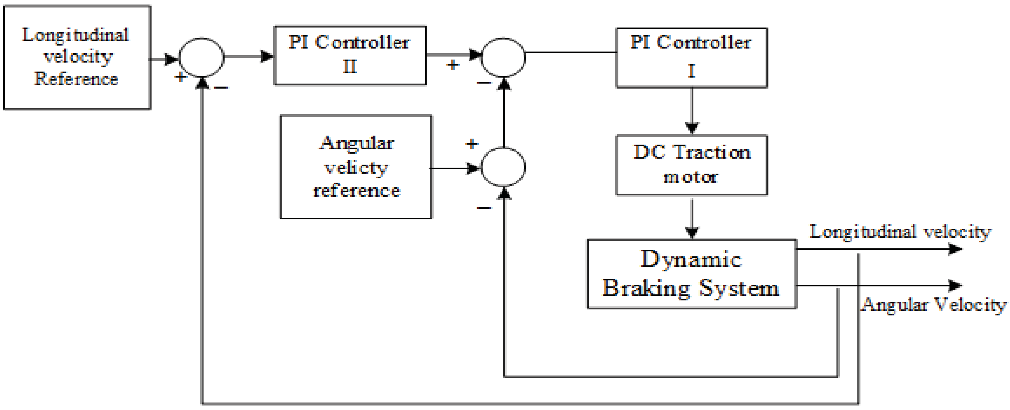

Fig. 3 Dynamic braking system based on cascade control structure

IV. SHUNT EXCITED DC TRACTION MOTOR MODELING

In this part, we present dynamic equations for a shunt excited DC traction motor based on the equivalent which is shown in Fig. 4 [9], [10] and we study its performance in dynamic braking system with the cascade control structure that is introduced in Fig. 3.

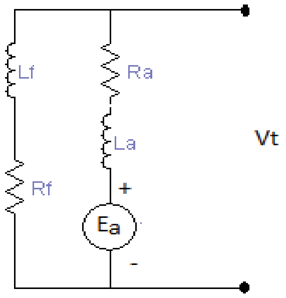

Fig. 4 Equivalent circuit of shunt excited DC traction motor

The equations are defined as (8)-(11):

$$V_t = R_f I_f + L_f \frac{dI_{Lf}}{dt} \tag{8}$$

$$V_t = E_a + R_a I_a + L_a \frac{dI_{La}}{dt} \tag{9}$$

$$\tau_M = f(I_a, I_f) \simeq K_{sh}.I_a.I_f \tag{10}$$

$$E_a = f(I_f, \omega) \simeq K_{sh}.I_f.\omega \tag{11}$$

τ_m is the motor torque which is applied to the wheel-set of locomotive during the braking process. V_t is the input voltage of DC traction motor and E_a is the armature voltage. R_a and R_f are the resistance of the armature and the field, L_a and L_f are the inductance of the armature and filed of traction motor. The armature and field current are defined as I_a and I_f in the equations and ω is the angular velocity of the traction motor.

TABLE II
DC MOTORS PARAMETERS

parameters	abbreviation	value
R_f	Field resistance	1.430 Ω
L_f	Field inductance	0.23 H
R_a	Armature resistance	1 Ω
L_a	Armature inductance	0.5 H
K_{sh}	Shunt excited DC motor constant	0.03 (Nm/A)
K_a	Separately excited DC motor constant	0.01 (Nm/A)

Simulation results by using MATLAB software for the open loop and closed loop system is shown in Figs. 5 and 6. In the open loop system, we can see the slipping after a few seconds of braking process. The wheel has been locked and the slip ratio is not good. In the closed loop system, by applying the proposed cascade control structure, dynamic braking system could track the desired velocity profile and control the amount of the slip ratio to prevent slipping phenomena.

Error of the reference longitudinal velocity ($velocity_{reference}$) and the longitudinal velocity ($velocity$) is defined as (12) and is shown in all the simulation results to have a good sense of tracking.

$$error = velocity_{refrence} - velocity \tag{12}$$

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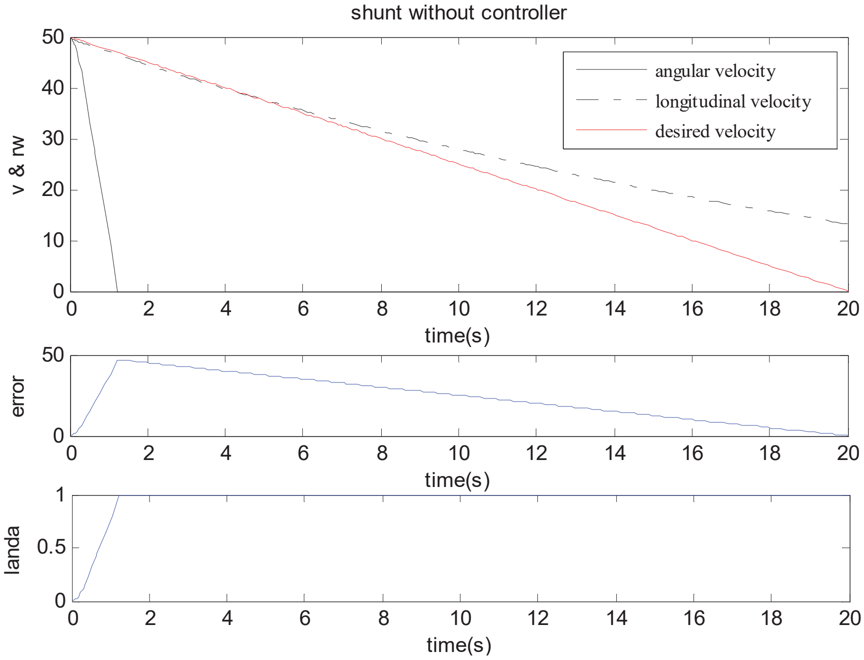

Fig. 5 Open loop response of the dynamic braking system for the shunt excited DC traction motor

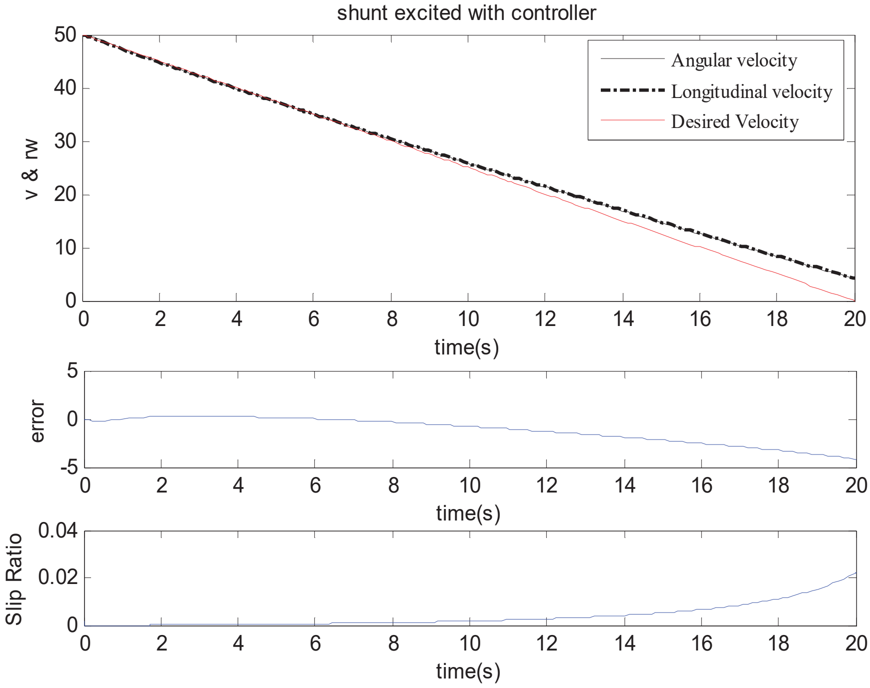

Fig. 6 Closed loop response of the dynamic braking system for the shunt excited DC traction motor

V. SEPARATELY EXCITED DC TRACTION MOTOR MODELING

According to the equivalent circuit of separately excited type of DC traction motors (Fig. 7), the corresponding dynamic equations are (13) and (14) [9], [10].

$$V_t = R_a I_a + L_a \frac{dI_{La}}{dt} \qquad (13)$$

$$\tau_m \simeq K_a . \phi . I_a \qquad (14)$$

In (13), ϕ is the magnetic flux of the motor and simulation parameters for separately DC traction motor are similar to shunt DC traction motor. The simulation results in open-loop and closed-loop system are shown in Figs. 8 and 9. As shown in Fig. 8, performance of the braking system, based on open-loop structure, is similar to the shunt DC traction motor and after a few minutes the wheel is locked which is not good and slipping happened during the barking process.

In the response of closed loop system based on the cascade control structure which is shown in Fig. 9, we can see that this control method can prevent slipping and tracking the desired velocity accurately and it causes to have a specify braking distance.

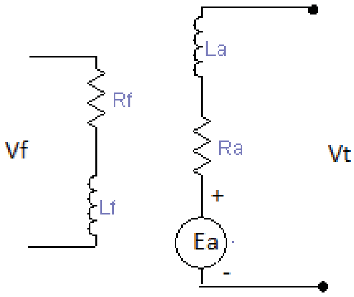

Fig. 7 Equivalent circuit of separately excited DC traction motor

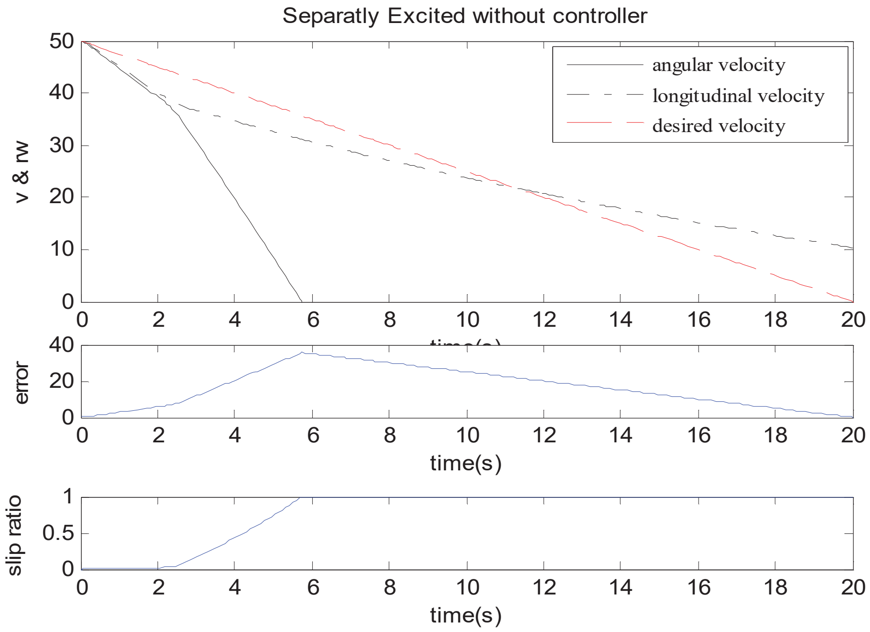

Fig. 8 Open loop response of the dynamic braking system for the separately excited DC traction motor

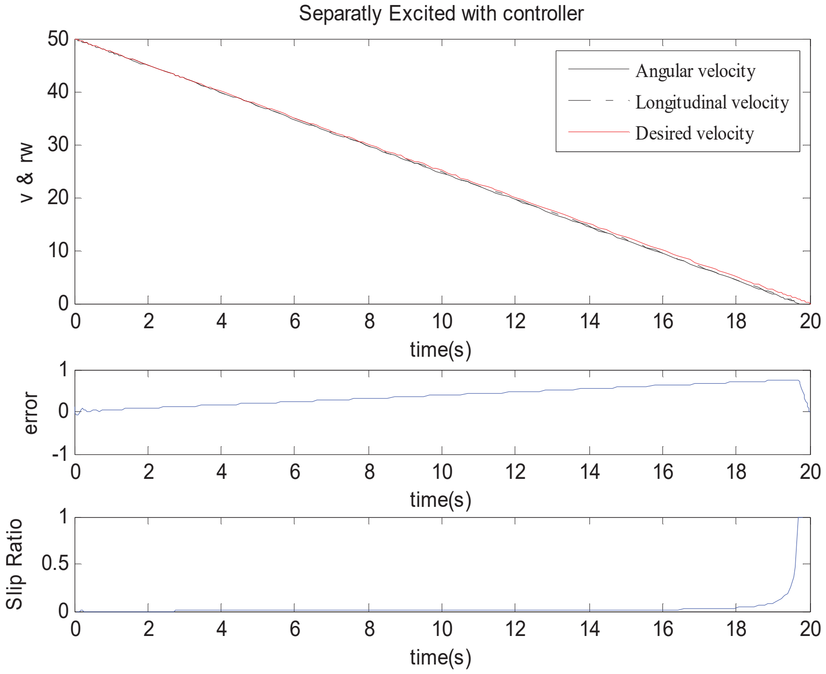

Fig. 9 Closed loop response of the dynamic braking system for the separately excited DC traction motor

VI. CONCLUSION

In this paper, we presented the new control structure based on cascade control method to slip control during the braking process in dynamic braking system of a locomotive. Also this paper, compared shunt DC traction motors and separately DC traction motors in dynamic braking system in the same conditions. Simulation results showed that stopping distance during the braking process in separately DC traction motors is smaller than the shunt DC traction motors and also in this type, tracking the desired velocity profile is better than the Shunt DC traction motors. Generally, cascade control structure could improve dynamic braking performance by controlling the slip ratio and tracking the desired velocity profile that can generate an accurate braking distance, too.

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